Emission and amplification of mid-infrared radiation in quantum well structures under generation of near-infrared light

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Abstract. Physical principle of population inversion of electrons between subbands under the electron-hole pair injection into the i-region of p-i-n heterostructure with quantum wells is proposed. The important features of this principle are the simultaneous generation of intraband ($h\nu \gtrsim E_g$) radiation of near-infrared range and presence of "metastable" level. Spontaneous mid-infrared radiation ($\lambda \simeq 10 \ldots 20 \, \mu$m) is observed from laser structures with InGaAs/GaAs quantum wells. The near-infrared laser diode structures with composite waveguide confining both near-infrared and mid-infrared radiation is designed and grown.

Introduction

The development of quantum cascade lasers [ ] based on modified idea suggested in [ ] and the development of "fountain" lasers with optical pumping [ ] are the great achievements of semiconductor physics in last years. However the realization of quantum cascade lasers is a very complicated technological problem and wide use of "fountain" lasers is limited by optical pumping.

In present work the principle of population inversion of electrons in quantum wells under the electron injection into i-region of heterostructure is considered. The described phenomena permit to develop new mid-infrared (MIR) lasers based on interlevel optical transitions of electrons.

There are three peculiarities of proposed principle. First of all the intraband inversion for QWs is achieved with the help of current injection of electron-hole (e-h) pairs. Then, the second important condition of realization of intraband population inversion (PI) for QWs is the presence of three energy levels and long electron lifetime on upper third level, so this level can be called as "metastable" one. This "metastable" level can be formed by selection of the configuration and parameters of QW (for example, choosing the shape of well as a rectangular funnel). The important role here belongs to the dependence of probability of intersubband electron transitions with emission of polar optical (PO) phonons on extent of wave function overlapping in different subbands and wave vector of emitted phonon. The third condition is simultaneous generation of near-infrared (NIR) radiation ($h\nu \gtrsim E_g$). In this case at rather large current $J > J_{th}$ (J_{th} — threshold current for NIR stimulated emission) the generation of MIR radiation is possible. In QWs with three levels NIR stimulated emission directly does not lead to PI. But its role is very important: NIR stimulated emission supports the constant electron concentration on lower level under
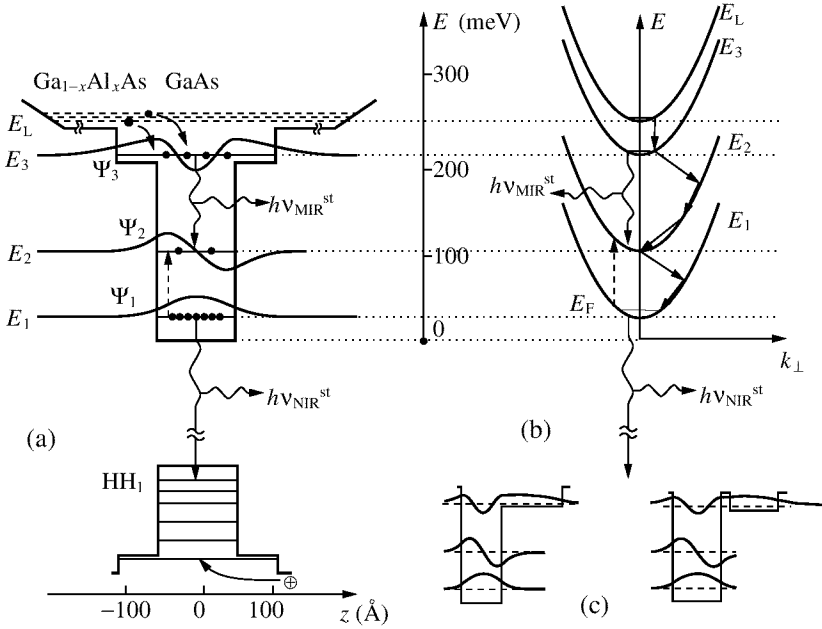
Fig. 1. (a) The diagram of electron transitions in quantum well placed in i-layer of laser n^+-i-p^+ heterostructure, energy levels E_i and electron wavefunctions. (b) The diagram of main inter- and intrasubband electron transitions with emission of optical phonons. (c) The profile of QW providing minimal overlapping the electron wavefunctions, belonging to the upper and two lower levels.

strong current $J > J_{th}$. This fact does not allow to break intraband PI with increase of $e-e$ interaction with current.

1 Principle of intraband population inversion

Let us consider for example n^+-i-p^+ heterostructure with undoped i-layer, having quantum well in the shape of funnel in its center (Fig. 1(a)).

Choosing the well parameters one can obtain the energy distances between levels as it is shown in the Fig. 1.

The injected into i-region electrons get onto the quasidiscrete levels in above barrier region and then they are captured by QW levels E_1, E_2, E_3 as a result of interaction with optical and acoustic phonons or after the elastic scattering by interface roughness.

In the stationary (but nonequilibrium) conditions the electron concentrations on the levels can be found out from system of rate equations, taking into account only main processes:

$$\eta J A_3 - N_3 W_{23} - N_3 W_{13} - N_3 (\tau_{\nu 3}^{sp})^{-1} = 0 \tag{1}$$

$$\eta J A_2 + N_3 W_{23} - N_2 W_{12} - N_2 (\tau_{\nu 2}^{sp})^{-1} + \beta_{12} N_1 = 0 \tag{2}$$

$$\eta J A_1 + N_3 W_{13} + N_2 W_{12} - N_1 (\tau_{\nu 1}^{sp})^{-1} - \beta_{12} N_1 - B_1^{st} N_\nu = 0, \tag{3}$$

where N_1, N_2, N_3 are the surface electron concentrations at levels 1, 2, 3; $\tau_{\nu i}^{sp}$ is the electron lifetime at level E_i relatively for interband radiative recombination under spontaneous emission in QW: electron in conduction band $\rightarrow$ hole in valence band; N_ν is the photon

density; B_1^{st} is a proportional coefficient. The last term in (3) describes the depopulation of level 1 due to stimulated NIR radiation. This term is significant at current J exceeding threshold current J_{th} for NIR radiation generation. Under $J > J_{th}$ this term is proportional to $(J/J_{th} - 1)$. Terms $\beta_{12} N_1$ take into account the thermally ejected electrons, $\beta_{12} = W_{12} \exp\left(-\frac{E_2 - E_1}{k_B T}\right)$. Coefficient η describes the part of electrons reaching QW region; A_1, A_2, A_3 are the coefficients determined the electron stream onto levels E_1, E_2, E_3. Lastly, W_{ij} are the probabilities of the transitions from level j to the level i under the interaction with optical and acoustic phonons and interface roughness. We shall consider low temperature $k_B T \ll \hbar\omega_0$ ($\hbar\omega_0$ is PO phonon energy) and take into account only processes with emission of PO phonons.

Calculating the probabilities of inter- and intrasubband electron transitions with emission of optical phonons we have obtained: $W_{13}, W_{23} \ll W_{12}$, $A_1, A_2 \ll A_3$. This is connected with weak overlapping of wavefunctions for appropriate levels and also with small value of phonon wavevector for transitions $E_2 \to E_1$ and $E_L \to E_3$. So, we can call level 3 as "metastable".

The movement of electrons between energy states of QW is shown in Fig 1(b). Fig. 1(c) represents possible well configuration providing weak overlapping the wavefunctions at level 3 and levels 1, 2.

Solving the system (1) and (2) we obtain:

$$N_3 - N_2 = \eta J \left(A_3 \frac{W_{12} - W_{23}}{W_{12}(W_{13} + W_{23})} - A_2 W_{12}^{-1} \right) - N_1 e^{-\frac{E_2 - E_1}{k_B T}}. \qquad (4)$$

Last term in (4) may be neglected at $T < 200$ K and extent of PI can be evaluated as $N_3 - N_2 = 6 \times 10^8 J/J_{th}$ cm^{-2}.

We calculated optical gain under direct optical transitions between subbands 2 and 3. If optical confinement factor is 10^{-2} (one QW in i-layer), mirror reflection coefficient is 0.3 and resonator length is 1 mm then the threshold current of MIR stimulated emission $J_{th}^{MIR} = 20 J_{th}^{NIR}$. Use of set of QWs may essentially improve the situation. So, if the number of QW is 10, $J_{th}^{MIR}/J_{th}^{NIR} = 2$.

2 Experimental results

The first investigation of MIR intraband spontaneous emission from NIR laser diode structures with QW in active layer was carried out in ordinary structures with 0.3 μm wide waveguide and In$_{0.2}$Ga$_{0.8}$As/GaAs QW [4]. Intensity of MIR radiation was very small due to strong free carrier absorption of MIR radiation in doped regions. In order to increase this intensity we have designed the heterostructure with composite waveguide. This waveguide confines both MIR and NIR radiation. The diagram of the structure is shown in Fig. 2.
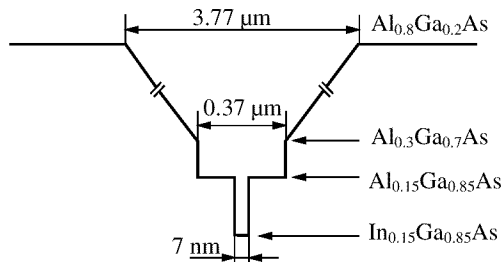

Fig. 2. The band diagram of laser diode structure with wide waveguide.

The structure was MOCVD grown. The active layer for NIR lasing contains 7 nm $In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As$ QW. The width of waveguide for NIR radiation is 0.3 μm. Undoped graded regions of length 1.7 nm form the waveguide for MIR radiation. We found NIR lasing in this structure. The great width of undoped layers leads to the large value of threshold current. The J_{th} values for four-side cleaved samples where external losses are negligible was about 500 A/cm^2. The results of study of MIR spontaneous radiation due to intraband electron transitions in this structure are presented.

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